"ADVANCE AND RELIEVE" MINING, A METHOD TO MITIGATE THE AFFECTS OF HIGH HORIZONTAL STRESS ON THE MINE ROOF

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ABSTRACT

At a mine in central PA, high horizontal stresses have caused long running roof falls resulting in hazardous conditions for the miners and the premature abandonment of panels. Because of these conditions, the mine requested assistance of the National Institute for Occupational Safety and Health (NIOSH) in utilizing the "advance and relieve" method to mitigate the affects of horizontal stress on the mine roof. "Advance and relieve" mining involves the removal of a pillar or a portion of a pillar during development, thereby creating a cave along one side of the panel. Following cave development, the horizontal stress is relieved over the workings adjacent to the cave in the active panel. The mine has used this system in three panels with a significant reduction in stress damage and no large roof falls.

INTRODUCTION

When ground control problems are caused by horizontal stress, there are several approaches that can be used to combat the conditions that develop. One is to relieve or reduce the stress so that it causes less damage to the rock in the immediate vicinity of the mine openings. Horizontal stress relief can be accomplished by intentionally caving the roof that then in theory creates a stress shadow or a zone of reduced stress. Other mine openings driven in this stress shadow may suffer less damage. The geometry and location of the reduced stress zone depends on a number of factors including the cave height and cave orientation with respect to the horizontal stress direction.

Longwall mining generates a cave with an accompanying stress shadow (Mark et al., 1998 and Mucho and Mark, 1994). However gateroad development is usually too far from the cave to be affected by the reduced stress. There are also zones around the longwall cave where stress concentrations are generated from the horizontal stress (Mark et al., 1998, Dolinar et al., 1996 and Sue and Hasenfus, 1996). In room and pillar operations, retreat mining that develops a cave will also create horizontal stress relief zones. However, unless properly sequenced, development mining may not be protected by the cave. In the worst case, development could be through zones of horizontal stress concentrations generated by the cave, thus increasing the likelihood of encountering stress related problems.

A stress shadow can also be created by using a sacrificial opening or entry driven into the stress field in advance of the adjacent entries. With the failure of this opening, the following adjacent entries should be protected from the effects of high horizontal stress. However, it is difficult to mine and maintain a sacrificial opening due to slower development and substantial supplemental support requirements. A modification of the sacrificial entry concept was conducted as an experiment at a mine in West Virginia. In this experiment, the center entry of a 3 entry gateroad was mined in an arched configuration to a height 4.1 m (Aggson 1988 and Aggson and Mouyard, 1988). The entry was then lined with steel sets and lagging. The roof subsequently failed and created an opening with an effective height of 7.6 m above the floor. The extent of the stress relief zone was at least 25 m. This extensive stress relief zone could not be explained by the rock acting as a continuous, elastic, homogenous material. However, underground observations and numerical modeling, showed that slip on horizontal bedding planes was a significant contributor in forming such a large stress relief zone.

Another approach that can be utilized especially in room and pillar mining is to create a cave adjacent to a panel or set of entries during development. This mining system is called the "advance and relieve" method. The first documented case of using the "advance and relieve" mining method in the U.S. was at the Sargent Hollow Mine, Wise County, VA (Chase et al., 1999). The mine had experienced poor roof conditions and directional roof falls associated with high horizontal stress and roof geology that was susceptible to stress damage. The mine used the system on one panel and on a portion of a second panel successfully. The investigation reached 4 main conclusions: (1) the roof control problems associated with high horizontal stress at this mine could be significantly reduced by "advance and relieve" mining, (2) a knowledge of the stress direction is critical when determining a panel orientation and a pillaring plan, (3) the degree of stress relief and the extent of the stress relief zones is a three dimensional problem, and (4) the face areas will be more quickly relieved the closer they are to the pillared out workings, however, this will reduce the safety zone that protects the working faces from the cave.

The present study was conducted at the Tanoma Mine, Tanoma Mining Company, Inc., a room-and-pillar coal operation that was experiencing roof cutters and long running roof falls caused by horizontal stress. Because these roof conditions created hazards for the miners, and caused several productions panels to be abandoned prematurely, the mine requested assistance from the National Institute for Occupational Safety and Health (NIOSH) in applying the "advance and relieve" method to reduce the affects of the horizontal stress during panel development. This paper presents information on the application of the "advance and relieve" system at the mine and discusses the important ground control issues related to the method.

TANOMA MINE

The Tanoma Mine, is located about 16 km northeast of Indiana, PA. For this study, the area of interest is the E mains and panels that are shown in plan view in figure 1. To date, 15 panels have been driven south off the mains, generally in the S 30° E direction, and 7 panels have been driven on the north side of the mains in the N 30° W direction. To develop the panels, a continuous haulage system is used with crosscuts driven at 60° angles off the entries. Panels are developed using either a 4 or 5 entry system. In the panels, crosscuts are on 18.3 m centers and entries are on 24.4 m centers. The entry width is 5.5 m. The primary roof support is either a 1.5 m, # 5 or a 1.8 m, #6 fully grouted rebar installed on a 1.2 m row spacing with 4 bolts per row. Supplemental support consists of 2.4 m, #6 fully grouted rebar and 1.52 cm and 1.78 cm diameter cable bolts with lengths ranging from 3.7 to 6.1 m. In the mains, a shuttle car system is used for haulage and the entries and crosscuts are driven at 90E angles. The overburden depth over the E main section ranges from 180 to 270 m. Several mines in the area have been noted for directional ground control problems related to the horizontal stress (Barish, 1980, Bauer, 1990 and Krupa and Khair, 1991).

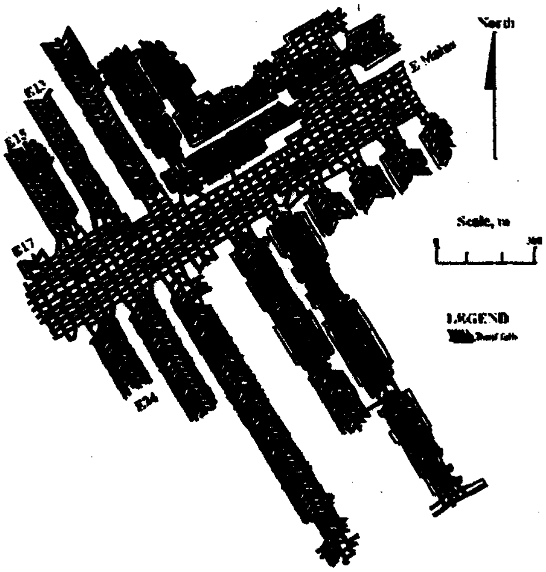

Figure 1. Plan view of E mains and panels showing long falls

Geology

The Tanoma Mine is in the Lower Kittanning or B seam and has a coal height of 1.2 m. The geology of the immediate roof in the E mains and panels consists of a gray or black shale to a depth of about 6.1 m. This shale is overlain by a competent sandstone that is generally 0.6 to 0.9 m thick. In areas, the shale will become silty especially above a depth of 4.6 m in the roof and near the sandstone unit. However, at times the sandstone may be within 3.0 to 4.6 m or closer to the seam. Figure 2 shows a typical geologic section of the mine roof.

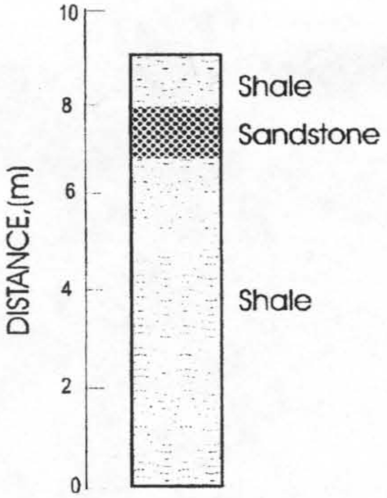

Figure 2. Roof geology in the E mains and panels

Ground Control Problems

In the E mains and panels, the mine has experienced directional roof control problems that are related to horizontal stress. The stress damage includes long running roof falls and cutters. Roof falls as long as 610 m and up to 9.1 to 10.7 m high have occurred generally in the northwest or southeast direction (figure 1). About 95% of the fallen roof is in the N 30° W orientation. Figure 3 shows the amount of fallen roof normalized by the drivage in a given direction. In the N 30° W direction (150° azimuth), over 5% of the drivage has failed while sightly over 2% of the drivage has fallen in the N 40° W direction (140° azimuth). In the other mining directions, less than 1% of the roof has fallen. These roof falls have occurred on both development and during retreat mining where falls occur just outby the cave. When the roof falls occurred during retreat mining the panels or portions of the panels would often be abandoned.

Mapping of the stress damage also indicates the directional nature of the roof problem by documenting more subtle roof damage in addition to roof falls (Mucho and Mark, 1994). This stress damage is in the form of cutters or gutters (figure 4). In the panels, most of the stress damage again occurred in the N 30° W entries. In panel E13 about 23% of the drivage had stress damage in the form of cutters or guttering. Ninety-five percent of this damage was in the N 30° W entries with 45% of the drivage in this direction suffering stress damage.

Although much of the stress damage occurred outby the faces after the roof had been supported, occasionally, damage occurred during face advance or prior to installation of the primary support. However, the majority of the roof falls occurred from a few days to several weeks after an opening was mined. About 50% of the roof falls in the N 30° W direction occurred in the belt entry whose width was usually wider than the other entries.

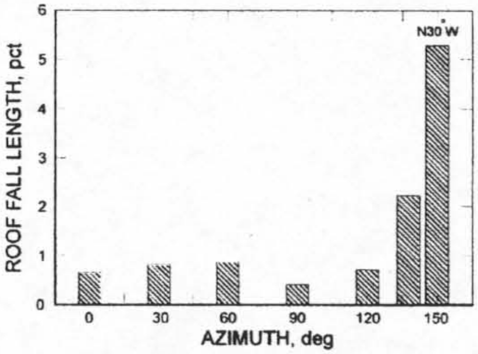

Figure 3. Direction of failed roof normalized by drivage in a given direction

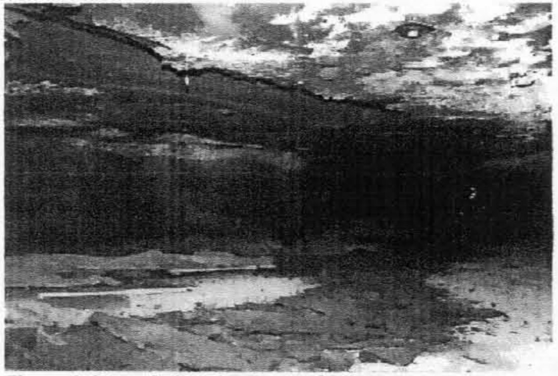

Figure 4. Stress induced cutter roof failure

Direction and Magnitude of the Horizontal Stress

Initially, to determine the direction of the maximum horizontal stress, the pattern of the roof falls was used. The highest percentage of roof falls occurred in the N 30° W direction (figure 3). This would indicate a maximum horizontal stress from N 60° E. However because there was no drivage between N 30° W and north, the actual maximum stress direction could be more toward the east. Therefore, the maximum stress direction could fall between N 60° E to N 80° E. It was assumed that the maximum stress could not be any closer to the east-west direction or to the N 50° E direction because of the limited amount of falls perpendicular to those directions. Therefore, a N 70° E direction was selected as the direction of the maximum horizontal stress for the design and evaluation of the "advance and relieve" mining method.

To further define the maximum horizontal stress orientation and determine the stress magnitude, in situ stress measurements were also made using both hydraulic fracturing and overcoring with the USBM 3 component borehole deformation gage (Bickel, 1993 and Enever et al, 1990). The hydraulic fracturing was done with a minifrac system from an underground borehole in the sandstone above the coal at a depth of 7.9 m in E24 panel on the south side of the E mains (Su and Hasenfus, 1995). The horizontal stresses in the sandstone from this measurement were the maximum horizontal stress P= 44.2 MPa from N 87° E and the minimum horizontal stress Q= 26.7 MPa from N 3° W.

Overcoring stress relief measurements were made at a site in E mains just outby the entrance to E15 panel. Measurements were attempted at depths from 4.6 m to 7.0 m. Only one measurement in the shale was successful. The measurement in the shale was at a depth of 5.2 m and the calculated stresses were P = 13.6 MPa from N 78° W and Q = 11.8 MPa from N 12° E. An elastic modulus of 23.4 GPa was used to determine the stress. In the sandstone, the core disked during overcoring.

Clearly a substantial stress was measured by hydraulic fracturing in the sandstone that is further indicated by the core disking (Aggson, 1978). The measured horizontal stress in the shale is much higher than the expected vertical stress of 5 MPa. Surprisingly, the measurements in the shale found that the horizontal stress was nearly uniform with maximum stress only 10% greater than the minimum stress. However, the directional nature of the roof falls and the mapped stress damage features indicates the existence of a more highly anisotropic stress field. Therefore, based on all available information, the maximum horizontal stress direction was assumed to be N 70° E for design purposes.

THE "ADVANCE AND RELIEVE" METHOD

Because of the extent of roof falls and stress damage, the mine decided to try "advance and relieve" mining. This mining system would be used on 3 panels on the north side of E mains, panels E15, E17, and E19 (figure 1). The "advance and relieve" method involved the extraction of a pillar and a portion of the barrier on one side of the panel during development. Figure 5 shows a portion of the E15 panel with the right side of the panel being pillared. The pillar and barrier were mined just outby the faces. With the pillar extraction, a cave was created along the right side of the panel. In this panel layout, the faces were driven 1 to 2 crosscuts ahead of the cave.

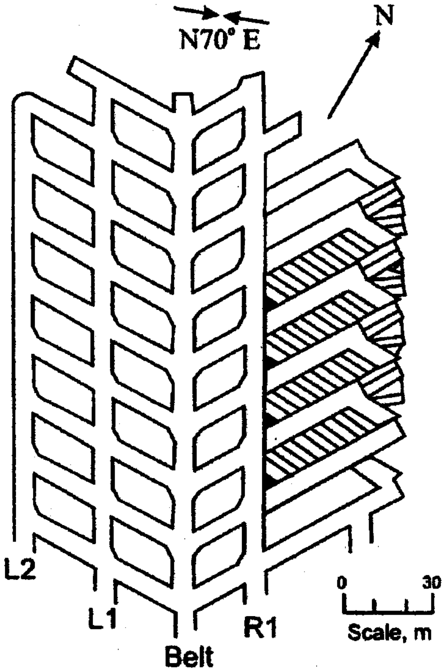

Figure 5. Plan view of E15 panel showing "advance and relieve" pillaring

Panel Layout and Pillar Plan

The panels and cave were developed in the N 30° W direction and therefore at a 100° angle or nearly perpendicular to the maximum horizontal stress from N 70° E. With this panel orientation, the maximum zone of protection that should occur in front of the cave would develop when the pillaring was conducted on the right side of the panel. However, the advancing faces would still not be stress relieved because the stress shadow lagged one or two crosscuts behind. At the Tanoma Mine, because the roof falls and much of the stress damage usually occurred several days after mining, stress relief of the faces was not critical. Figure 6 shows a plan view of panel E15 with the assumed stress pattern that should develop around the cave in two dimensions.

In E15, the "advance and relieve" mining did not begin until after the panel had been advanced 275 m. At the Tanoma Mine for a 5 entry panel, entries were designated from left to right as L2, L1, belt, R1 and R2. The R1 entry was adjacent to the cave (figure 5). The first pillar that was outlined by the "advance and relieve" system was not mined. This allowed for the modification of the panel layout from the original 5 entry to the 4 entry configuration with extension of mining into the barrier.

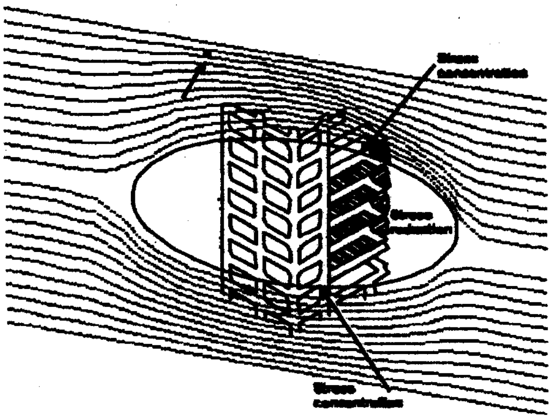

Figure 6. Plan view of stress distribution around pillaring and cave with reference to a N 70° E direction of the maximum horizontal stress

Figure 7 shows the original extraction plan. The plan called for the pillar to be extracted from a room developed from the R1 entry. This original panel layout had crosscuts on 18.3 m centers with the length of the extracted pillar of approximately 30 m. The room length and extent of extraction into the barrier was controlled by the reach of the continuous haulage system which was 79 m.

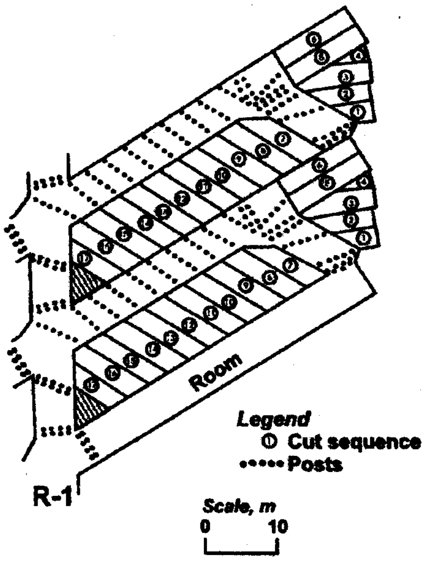

Figure 7. Original pillar plan used in E15 panel

A cut back entry at the end of the room was mined and supported to complete the pillar. This allowed for adequate ventilation and complete pillar extraction. Once the cut back was completed, the mining sequence was to first cut into the barrier and then extract the pillar. The pillar was mined from the barrier toward the R1 entry. Only a small pillar remnant about 3.0 to 4.6 m wide was left along the R1 entry next to the cave. With this system, a cave quickly developed that was about 30 to 37 m wide and that extended from the pillar remnant to the barrier. At several intersections the cave did extend into the R1 entry. However, with this plan, the cut back entry was very difficult to mine because the entry was subjected to severe roof damage from the horizontal stress concentration. Figure 8 shows the stress concentration that developed around the cut back entry. After 6 pillars were mined using the first plan, a second pillaring plan was developed to address this issue.

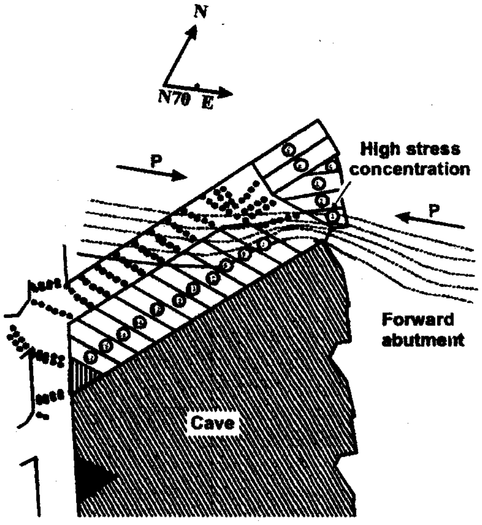

Figure 8. Forward stress abutment and concentration with respect to original pillaring plan

Second Pillar Plan

The second pillar plan eliminated the cut back entry, substituting a notch cut into the pillar parallel to the R1 entry from the outby room prior to the pillar extraction (figure 9). This notch allowed for a cut through of the pillar during the early stages of pillaring for ventilation and allowed for the full pillar width to be mined. Normally, the notch would be bolted with only 2 rows of bolts inby the rib line. With this second pillaring plan, the horizontal stress appeared to be concentrated near the notch and on the inby half of the crosscut where stress damage in the form of cutters still occurred (figure 10). However, the intervening coal pillar between the notch and the crosscut reduced the combined affects of the two openings on the stress concentration. During pillar extraction, the cuts that mined into the notch, cuts 4 and 5 resulted in the roof caving from the notch inby to the barrier. After this cave, there were few problems encountered with the extraction of the remainder of the pillar.

Essentially, when the pillar was now mined, a portion of the horizontal stress concentration was now over a section of the pillar to be extracted. However, instead of being a problem for development, the stress concentration now assisted in generating a cave. Not completely outlining the pillar by development mining at the notch was another essential feature of this design. This minimized or eliminated the potential for a roof fall at this location that could develop and adversely affect pillaring and face development. Later, the second plan was adjusted slightly where a bigger pillar remnant with an average width of 9 m was left along the R1 entry. With the larger remnant, the R1 entry was kept open, where previously the roof had caved in some of the intersections.

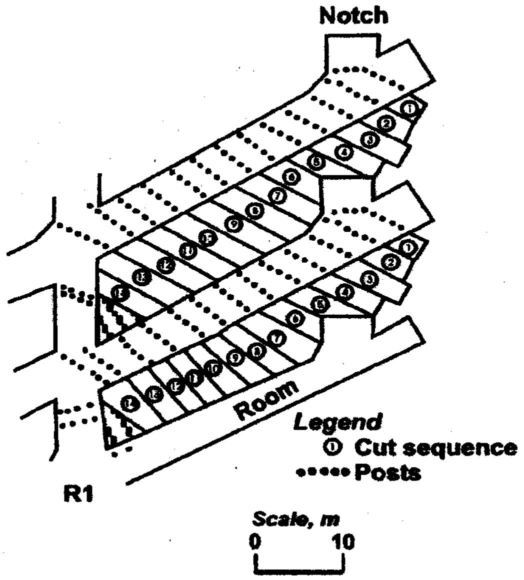

Figure 9. Second pillaring plan used in E15 and E17 panels

The second pillaring plan was used for 16 additional pillars in the E15 panel and for the adjacent E17 panel where 25 pillars were mined (figure 11). With E17, pillaring began just 75 m inby the mains and 200 m outby the start of pillaring in E15. Again, a pillar and a standing room were left outby the cave.

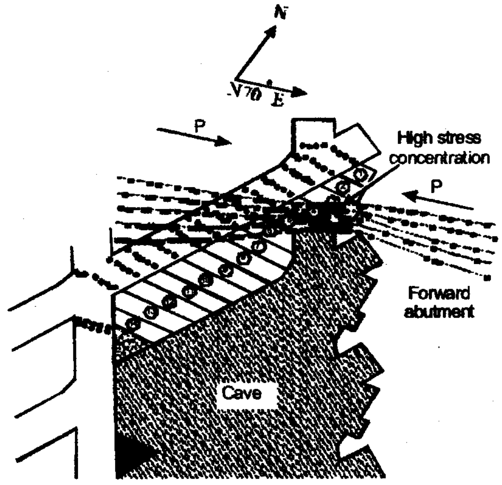

Figure 10. Forward stress abutment and concentration with respect to second pillaring plan

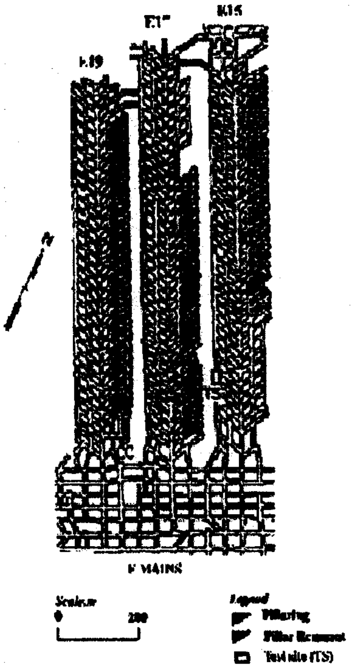

Figure 11. Plan view of panels E15, E17 and E19 showing location of test site

Floor Heave

With the start of "advance and relieve" pillaring in both panels E15 and E17, significant floor heave developed. For these panels, the floor geology consisted of 0.3 m to 0.6 m of shale underlain by 1.2 to 1.5 m of fireclay while the overburden averaged 210 m. Figure 12 shows typical floor heave that occurred. Systematic roof to floor convergence measurements were made in the intersections of the belt, L1 and L2 entries along the length of each panel.

Figure 12. Floor heave experienced in E15 panel

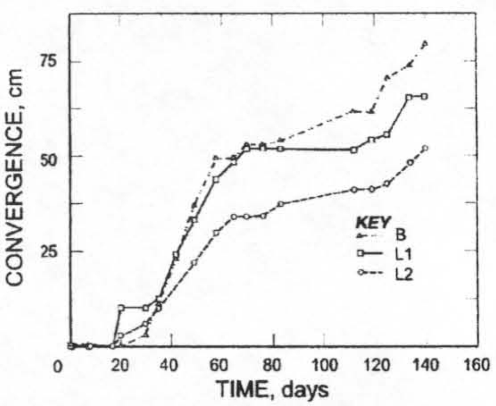

Figure 13. Floor heave rates across E17 panel

The maximum floor heave occurred in both panels during the first 245 m of "advance and relieve" pillaring. In E15 the average heave rate in this panel section was 0.6 cm/day, while in E17 the average rate was 0.96 cm/day. These rates were maintained for periods of up to 40 to 60 days before leveling off. In places, 50 to 75 cm of floor heave resulted. The floor heave occurred across the panel width and was not confined to the area adjacent to the cave. Figure 13 shows the pattern of floor heave over time across the E17 panel 60 m inby the start of pillaring. The accelerated rate of floor heave shown in figure 13 after 115 days is the result of retreat mining in the panel. The variable initial rates between 20 and 30 days may reflect the failure of the hard shale layer.

Because of the floor heave, an evaluation was made of the pillar stability and the pillar loads using Analysis of Retreat Mining Pillar Stability (ARMPS) (Mark and Chase, 1997). In the panels, the stability factor of the pillars between the belt and R1 entry was 1.16 while the average stress on these pillars were 20 MPa. For these pillars, the crosscut spacing was 18.3 m and entry spacing was 21.3 m. The entry spacing for the pillar between the belt and the L1 entry was 24.4 m.

The heave necessitated removal of the floor in sections of the panels in both the belt and the L1 travel way outby the face. Because of the floor heave problem, the pillaring plan and pillar and panel design in the E19 panel were altered with the third pillar plan discussed below.

Third Pillar Plan

To address the floor heave issue, a third pillaring plan and a new panel design were developed and implemented in panel E19. The size of the pillars in the panel were increased by extending the distance between crosscuts to 21.3 m. Instead of a pillar remnant as was left in E15 and E17, a pillar was now left between the cave and the R1 entry that was on average 12.2 m wide. Figure 14 shows this third pillaring plan. A double notch was used to assure that a cut through was made during pillaring for both ventilation and caving. Besides the change in pillar dimensions, the width of the caved zone was decreased to about 24.4 to 27.4 m.

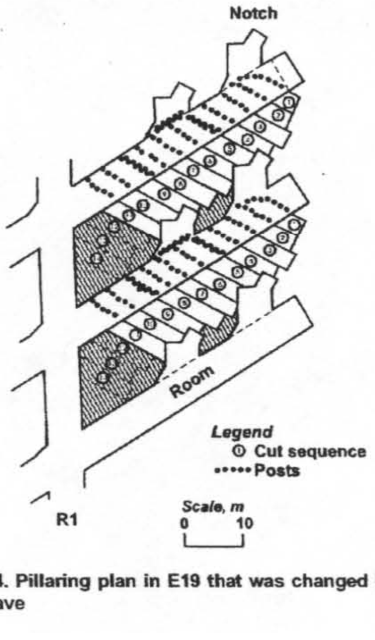

Figure 14. Pillaring plan in E19 that was changed because of floor heave

Using the ARMPS analysis, the pillar between the R1 and belt now had a stability factor of 2.1, with an average vertical stress of 12.4 MPa. The pillar adjacent to the cave had a stability factor of 1.7 with an average vertical stress of 15.2 MPa. The larger pillar along the cave kept the R1 entry open for ventilation. Although floor heave still occurred in E19, the average rate of floor heave was only 0.30 cm/day. This rate can be compared to that in panel E21 a panel adjacent to E19 , which was at the same depth and had essentially the same pillar and panel design as E19 except that instead of pillaring on advance, an R2 entry was developed. The floor heave rate averaged 0.23 cm/day across the E21 panel. Essentially, the floor heave in E19 was only slightly more than that expected from a panel with no "advance and relieve" mining.

With a weak floor, floor heave must be considered when adopting the "advance and relieve" method because the openings will be subjected to an increased vertical abutment from the cave for the life of the panel. This additional time allowed for increased floor heave. Further, this floor heave developed well outby the face and was worse at the start of the panel.

In the E19 panel during "advance and relieve" pillaring, no stress damage was observed even at the faces. Also, caving was not as complete as before and lagged further outby the pillaring. Typically the cave stayed behind the pillar line by about 3 to 5 crosscuts. Therefore, inby the cave, a large mined out area 27 m wide by to 60 to 90 m long remained open. After the first 6 pillars were extracted, the final 18 pillars in the panel when mined were behind the retreat cave in panel E17.

Extracted Pillar Layout and Cut Sequence Direction

Besides the pillar plan developed to deal with the forward abutment, the layout and direction of the extracted pillar with respect to the cave and the stress concentration generated by the forward abutment also appears to be important to the successful extraction of the pillar. In this case the long dimension of the pillar was across the cave front as was the direction of the cut sequence.

This pillar layout and cut sequence allowed for the high stress concentration to be intersected only in the cuts toward the back portion of the pillar furthest from the R1 entry, cuts 4 and 5. After these cuts, there appeared to be less stress in the roof. If the cave initiated as usual after these cuts, this would further reduce the stress in the roof for the remaining pillar cuts. Therefore, for the cuts after 4 and 5, the roof may not have been subjected to the highest horizontal stresses or full abutment stress thus making extraction of the rest of the pillar easier (figure 10). Also, with this pillar design, the high stress concentration was kept in the outer portion of the pillar extraction room and away from the rest of the panel.

HORIZONTAL STRESS ABUTMENTS AND REDUCTION ZONES

"Advance and Relieve" Stress Monitoring

The horizontal stress changes that occurred from the "advance and relieve" mining in E17 were measured by instruments placed at a test site in the L2 entry of E15 panel. Figure 11 shows the location of the test site with respect to E17 where the distance from the cave to the instrumentation was 37 m. Two types of instrumentation were used, the USBM 3 component borehole deformation gage and the CSIRO hollow inclusion cell (Bickel, 1993 and Worotnicki and Wltopn, 1976). The borehole deformation gages were located at depths of 0.6,1.5, 3.1, and 4.6 m and the CSIRO cells at 1.5 and 6.1 m in the roof. The 6.1 m cell was in the sandstone roof unit.

Figure 15 shows the stress changes with time as the panel approached, then passed the test site for the gages at 0.6 and 3.1 m. The cave front position is also indicated on the graphs. On this figure, the largest stress reduction is ΔP and the smallest ΔQ. The orientation of the stress changes are given as the azimuth to the smallest stress reduction component ΔQ. A minus value represents a stress reduction while a positive value represents a stress increase. Although the data is not shown, at the 6.1 m depth there was a stress reduction of 8.3 MPa after the cave had passed the test site with an azimuth direction of 233°.

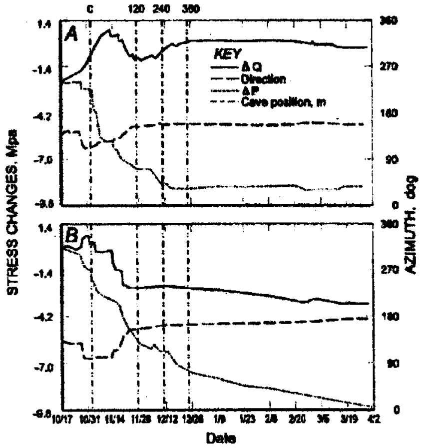

Figure 15. Horizontal stress changes measured at the test site. (A) 0.6 m depth and (b) 0.3 m depth. The azimuth direction is to ΔQ.

Forward Horizontal Stress Abutment

With cave initiation, a horizontal stress abutment was created in front of the cave (figures 6 and 8). The damage in the cut back entry which required a pillar plan modification previously mentioned was one indication of this abutment. Even with the second pillaring plan, the outer half of the room used to extract the pillar in front of the cave sustained stress damage. However, the location of this damage was generally predictable though requiring at times longer bolts to be installed. Also, these areas were subjected to these stress conditions for only a short period of time which minimized the damage that could be done.

This forward horizontal stress abutment was seen by the increase in stresses as the cave front approached and passed the test site. At 37 m from the cave, stress increases ranged from 1.4 to 5.5 MPa. This stress increase began when the cave was 60 m outby the test site. At the 0.6 m level, the roof conditions did not allow this added stress to be sustained which quickly dropped to show a stress reduction. At other depths, the stress concentration just sub parallel to the cave remained higher than the original levels.

Some roof damage did occur in the faces inby the cave, especially in the R1 entry where a cutter would normally develop from the crosscut at the cave front and progress inby toward the face of R1. About 74% of R1 received some stress damage in E15. This again was an indication of the forward horizontal stress abutment.

For the first 300 m of "advance and relieve" pillaring in E15, this stress damage was largely confined to the R1 entry. However, in the last 90 m of the pillared section of the E15 panel, cutters and guttering were seen in the other three entries. This damage occurred both at the face and outby the face in portions of the L2 entry that were not yet in the stress shadow. After the "advance and relieve" pillaring was halted to allow for connecting entries to an adjacent panel to be mined, this damage continued inby for the rest of the panel (a distance of another 120 m). In this section of the panel, guttering and severe roof damage occurred mainly in the faces. A roof fall did occur in the belt entry 30 m inby the cave. Both the E11 and E13 panels that were adjacent to E15 were terminated at the edge of this zone because of severe roof damage and roof falls. However, no roof falls occurred in the entries adjacent to the cave and the stress damage did not appear to get any worse. No roof control problems occurred during retreat mining in E15.

Rear Horizontal Stress Abutment

Roof damage in the entries and crosscuts in the panels just outby the cave was probably caused by the rear horizontal stress abutment (figure 16). This abutment did not advance with the mining, but remained stationary. In E15, the damage consisted of cutters that developed in the R1 entry from the cave outby for a distance of approximately 60 m. This stress damage was parallel to the length of the cave. Stress damage also occurred in the crosscut just outby the cave. A cutter ran across the belt entry then into the crosscut from the belt entry to the L1 and L2 entries. This was a narrow zone about 3 m to 5 m wide of fairly severe roof damage that crossed the entire panel at a right angle (figure 17). Because the rear abutment was stationary, the damage from this abutment appeared to be more severe than that resulting from the forward abutment. The damage parallel to the cave in the R1 entry was probably caused by the concentration of the maximum horizontal stress. However, the stress damage across the panel may have in part been caused by the minimum horizontal stress.

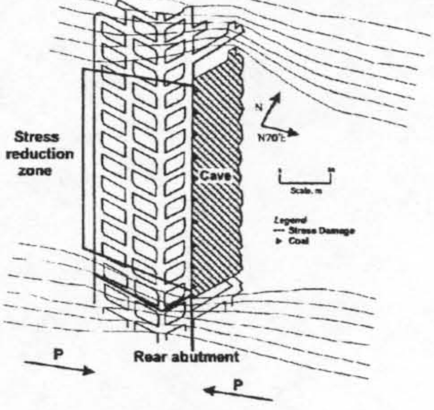

Figure 16. "Advance and relieve" panel with cave showing the forward and rear abutments and stress reduction zone

Figure 17. Rear abutment stress damage in L1 entry

To rehabilitate the damaged roof, cribs, posts and cable bolts were used as supplemental support in the R1 entry and across the panel along the narrow zone of damage. Similar, though not as severe damage was seen outby the cave in E17. Again supplemental support was used to control the stress damage. In E17 the damage approached but did not reach the mains.

Stress Reduction Zone

Stress relief began when the cave was across from the test site and was competed to a large extent when the cave was about 150 m inby. After the cave passed, the stress change measurements showed that there was a significant stress reduction in the shale below the sandstone in the direction of the cave that ranged from 5.5 to 8.3 MPa (figure 15). Based on the original stresses measured in the shale, this would represent between a 40 and 60% reduction in the horizontal stress. At the 0.6 m level, there was stress relief in both directions, though the reduction parallel to the cave was only about 2 MPa. Even in the sandstone at a depth of 6.1 m, there was a stress reduction of 8.3 MPa that represents about a 20% reduction in the horizontal stress. Further, evidence of the stress reduction is suggested by the fact that no roof falls occurred in E15, E17, and E19 panels adjacent to the caves during development of about 1,600 m of panel length.

Although there are no quantitative measurements as to the extent of the stress reduction zone that developed, there are a number of qualitative indicators that can be used to approximate the distance. In both the E15 and E17 panels, there was no increase in damage or any roof falls in the L2 entry as compared to other entries. Because of the lack of damage or any change in the level of damage which occurred in the L2 entry, it appears that some stress relief was occurring in that entry, a distance of 67 to 76 m from the cave. Further, in the E13 panel, the panel adjacent to E15, almost 33% of the L2 entry suffered stress damage including roof falls. Another indication of the extent of stress relief was that the stress damage in E17 was limited to the R1 entry and pillar crosscut outby the E15 pillaring. Little damage was seen inby where the E15 "advance and relieve" pillaring had begun. The distance from the cave in E15 to the R1 entry in E17 was about 150 m. During retreat mining of panel E13, in early December, test site instrumentation monitored 0.7 to 1.4 MPa of stress change as the pillar line passed. The distance from the E13 cave to the test site was about 120 m. Therefore the extent of the reduction zone appears to be between 75 to 150 m, sufficient to cover the panel width (figure 16).

Observations in the E19 panel provide further evidence that "advance and relieve" and retreat mining generated some stress reduction in an adjacent panel. The E19 panel had little or no stress damage while the cave lagged behind the pillaring. This may indicate that the horizontal stress had been reduced to some extent in E19 prior to mining by both the "advance and relieve" cave and the retreat mining cave in E17 that could have stress shadowed a portion of the E19 panel. A similar situation developed in the E17 panel where a section of the panel appeared to be in a stress shadow created by the "advance and relieve" cave in E15. However, for the "advance and relieve" sections in the three panels, only the last portion of the E19 panel was in a stress shadow developed by a retreat cave. Further, the use of the "advance and relieve" method in the E17 and E19 panels assured that the stress relieve zone would cover the entire panel width.

Because of the cave orientation with respect to the stress field, the faces were not relieved immediately but fell into the stress shadow 1 or 2 crosscuts behind the face (figure 16). In much of the development in the 3 panels, shielding the faces was not critical since immediate stress damage did not occur in the advanced workings. When this damage did occur at the faces such as at the end of E15, the damage was limited because the roof was exposed to the high stresses for only a short time. Once behind the cave, the openings suffered no further roof damage.

Cave Height and Stress Relief

Because the cave height in part controls the size of the stress relief zone, it is important to establish the geometric relationship between the cave height and stress reduction zone. Obviously, no direct measurements could be made on the cave height. However, to obtain an estimate of the cave height, measurements on the height of a long fall that had occurred in the in the N 30° W direction were made. The fall height from the top of the mined opening was about 9.1 to 9.8 m resulting in a total opening height between 10.7 to 11.3 m. This was assumed to be the height of the cave in the "advance and relieve" section. The height of the cave will be limited by the bulking of the caved material and not by the width of the cave as long as the cave width is sufficient to develop the failure (Bell, 1975). The height of the cave will usually be between 2 to 10 times the mining height with the higher heights achieved in weaker shales (Kendorski, 1993).

The width of the stress relief zone from the cave appears to be between 75 to 150 m. With a cave height of only 10.7 to 11.3 m this stress reduction zone was 7 to 14 times the cave height. Further, the extent of the stress relief can not be explained by the response of a continuous, homogeneous, elastic material. This implies that much of the stress relief must come from movement and slippage along bedding planes or other discontinuities (Aggson, 1988 and Aggson and Mouyard, 1988).

DESIGN CONSIDERATIONS FOR "ADVANCE AND RELIEVE" MINING

Based on this investigation, there are a number of ground control issues that must be considered when applying the "advance and relieve mining method. These issues include:

- Direction of horizontal stress- the maximum horizontal stress at the mine was nearly perpendicular to the panels. Therefore, the right side of the panels were pillared to maximize protection to development but the faces were not stress relieved immediately.
- Roof geology- the immediate roof at the mine consisted of a laminated shale that was susceptible to stress damage.
- Extent of stress relief zone- the stress relief zone extended across the width of the panel for a distance between 75 to 150 m or between 7 to 14 times the cave height.
- Forward horizontal stress abutment- a pillaring plan was developed that could mine into and advance this horizontal stress concentration. For the successful plans the pillar was not completely outlined by development.
- Rear horizontal stress abutment-this stress concentration was stationary and resulted in locally severe stress damage that required supplemental support and a sufficient distance between the cave and the mains.
- Pillar layout and cut sequence- the extracted pillar and cut sequence were across the cave front. This minimized the amount of pillaring in the stress concentration zone.
- Floor heave/ pillar size- with the weak floor, significant amounts of floor heave occurred because of the exposure time. However, a pillar and panel design was developed that significantly reduced the floor heave.

CONCLUSIONS

The "advance and relieve" mining system was an effective way to minimize stress damage and to prevent roof falls caused by high horizontal stresses. With this system a significant reduction in the horizontal stress in the panel behind the cave was achieved. However, to successfully apply this mining method requires that a number of ground control issues be addressed.

REFERENCES

Aggson, J.R., 1978. "Coal Mine Floor Heave in the Beckley Coalbed An Analysis", Pittsburgh, PA: U. S. Department of the Interior, Bureau of Mines RI 8274.

Aggson, J. R., 1988,"Geomechanical Evaluation of a Coal Mine Arched Entry", Soc of Min Eng., Littleton CO, 7 pp.

Aggson, J. R., 1988, "Mouyard DP. Geomechanical Evaluation of a Coal Mine Arched Entry", International Journal of Min and Geophy Eng., pp. 185-193.

Barish, K., 1980, "Truss Bolting On-Cycle in Jane Mine Lower Freeport Seam", 1st International Conference on Ground Control in Mining, Morgantown, WV, pp. 1-10.

Bauer, E. R., 1990, "Cutter Roof Failure: Six Case Studies in Northern Appalachian Coal Basin", Pittsburgh, PA: U. S. Department of the Interior, Bureau of Mines IC 9266.

Bell, F. G., 1975, "Site Investigations in Areas on Mining Subsidence", Newnes-Butterworths, London, 168 pp.

Bickel, B. L., 1993, "Rock Stress Determination from Overcoring-An Overview", Pittsburgh, PA: U. S. Department of the Interior, Bureau of Mines, Bulletin 694.

Chase, F.E., Mark, C., Mucho, T, P., Campbell, P. L., and Holbrook, D. A., 1999, "The Advance and Relieve Mining Method: A Horizontal Stress Control Technique", Proceeding of the 18th International Conference on Ground Control in Mining, Morgantown, WV, pp. 300-308.

Dolinar, D. R., Tadolini, S. C., and Blackwell, D. V., 1996, "High Horizontal Movement in Longwall Gate Roads Controlled by Cable Support Systems", Proceedings of the 15th International Conference on Ground Control in Mining, Golden, CO, pp. 497-509.

Enever, J. R., Wold, M. B., and Crawford, G. R., 1990, "Hydraulic Fracturing for Rapid Low Cost Stress Measurements in Underground Mines", The AUSIMM Proceedings, Parkville, Aus., pp. 19-24.

Kendorski, F. S., 1993, "Effect of High-Extraction Coal Mining on Surface Subsidence and Ground Water", Proceeding of the 12th International Conference on Ground Control in Mining, Morgantown, WV, pp 412-425.

Krupa, E. D., and Khair, W. A., 1991, "Assessment of Underground Structural Design", Proceeding of the 10th International Conference on Ground Control in Mining, Morgantown, WV, pp. 15-25.

Mark, C., and Chase, F. E., 1997, "Analysis of Retreat Mining Pillar Stability (ARMPS)", Pittsburgh, PA: U. S. Department of the Interior, Bureau of Mines, IC 9446 Proceedings of the New Technology for Ground Control in Retreat Mining, pp. 17-34.

Mark, C., Mucho, T. P., and Dolinar, D. R., January 1998, "Horizontal Stress and Longwall Headgate Ground Control", Min Eng, pp. 61-68.

Mucho, T. P., and Mark,C., 1994, "Determining Horizontal Stress Direction Using the Stress Mapping Technique", Proceeding of the 13th International Conference on Ground Control in Mining, Morgantown, WV, pp. 277-289.

Su, W. H., and Hasenfus, G. J., 1995, "Regional Horizontal Stress and its Effect on Longwall Mining in the Northern Appalachian Coalfield", Proceeding of the 14th International Conference on Ground Control in Mining, Morgantown, pp. 39-45.

Worotnicki, G., and Wltopn, R. J., 1976, "Triaxial "Hollow Inclusion" Gauges for Determination of Rock Stress In-situ", Proceedings of the ISRM Sypm. Investigation of Stresses in Rock, Advances in Stress Measurement, Inst. of Eng Pub. No. 4.